ARB Workshop Review

Light Duty GHG-Reducing Technology Cost Assessment

NESCCAF

April 20, 2004

MARTEC®

The Martec Group is a partnership of technical market research professionals.

Mission
To support client planning initiatives through technical and scientific product, market and industry analysis

Martec Snapshot
- Founded in 1984
- Principal practice areas:
  - *Transportation*
  - *Healthcare*
  - *Chemicals*
  - *Electronics*
- Offices in Detroit, Chicago, Frankfurt, Tokyo and Beijing
- The firm serves global automotive suppliers across all light and heavy-duty vehicle systems

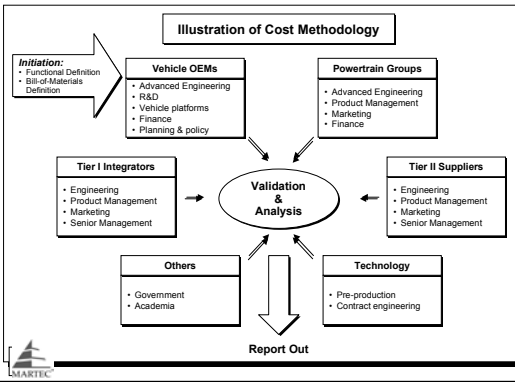
Martec evaluated incremental hardware costs at the vehicle manufacturer level.

In order to assure good connectivity with the modeling exercise for each technology, Martec was given:
- Written functional description from which a bill-of-materials was developed
- Reference technical specification from the industry
- Reference to an existing vehicle or architecture in production
- A particular supplier's implementation of the technology

The defined hardware content was costed in 2003 US dollars for the years 2009 and beyond assuming:
- A highly competitive, high volume purchasing environment
- At least 3 automakers employing the hardware at = 500,000 units annually
- At least 3 competent suppliers available to each automaker

Martec did not assume or attempt to calculate:
- Retail price equivalent
- Currently unknown advances in design and or manufacturing

Cost information was generated and cross-checked through a ground-up research effort.



Martec's results are reported in a matrix for calculation of *net* hardware costs vs. baseline.

A bill-of-materials description representing the functional application of each discrete technology is provided in the matrix.
- Costs to the automaker for the defined hardware are shown on a net basis
- Credits also are shown where a new technology would reduce baseline hardware content and cost

All study vehicles were required to meet Federal Tier 2 Bin 5 criteria emissions standards.
- Baseline as well as proposed future technology packages
- Lean-burn aftertreatment costs are expressed on a net basis vs. forecast 2009 stoichiometric Bin 5 baseline

Manufacturer-level costs not captured by Martec include:
- R&D, application engineering, calibration and controls development
- Warranty and possible recall costs associated with new technologies
- Capital and labor costs associated with vehicle level integration and assembly
- Cross-system impacts to vehicle level costs

Questions and Answers on Technology Cost Assessment

Technology	Technology Description - Hardware and Functionality	Vehicle Manufacturer Discrete Hardware Cost Delta 2009+ High Volume Variable Hardware Cost Delta Per Vehicle L4 V6 V6 V6 V8					
		2.2L DOHC 4V A4 FWD Cavalier (SC)	3.0L DOHC 4V A4 FWD Taurus (LC)	3.4L DOHC 4V A4 RWD Tacoma (ST)	3.3L OHV 2V A4 RWD Town & C (MV)	5.3L OHV 2V A4 AWD Sierra (LT)	
Engine Technologies							
DOHC from OHV	Substitution of DOHC 4V gas engine for OHV 2V gas engine of equal cylinder count. Content increase for Vee engine inlcudes: New cam drive, +3 camshafts, +2 valves per cylinder, cam bearing surfaces, extra valve seats and valve guides, roller cam followers. Assumes Al heads and Fe block for OHV and Al heads and Al block DOHC	-	-	-	$ 500	$ 600	
External EGR Credit	External EGR can be deleted if not needed or another means of exhaust dilution is available	$ (25)	$ (25)	$ (25)	$ (25)	$ (25)	
Variable Cam Phaser							
Single	**Line DOHC engines** -1 phaser on intake **Vee DOHC engines** - 2 phasers (1 on each intake bank) **Line or Vee OHV** - 1 phaser provides coupled functionality	$ 35	$ 70	$ 70	$ 35	$ 35	
Dual	**Line DOHC engines** - 2 phasers **Vee DOHC engines** - 4 phasers Practical solution for OHV engines undefined	$ 70	$ 140	$ 140	$ 140	$ 140	
Coupled	**Line DOHC engines** -1 phaser linked to both camshafts **Vee DOHC engines** - 2 phasers (1 linked to both camshafts on each bank) **Line or Vee OHV** - 1 phaser provides coupled functionality	$ 50	$ 115	$ 115	$ 35	$ 35	

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Variable Valve Lift (VVL)	Intake phasing costs must be added to all VVL and CVVL concepts.					
Discrete 2-step VVL (DVVL) - Electromagnetic (EM)	4 lost motion devices each operating 1 intake valve **pair** per cylinder. 4 actuators, drivers, harness. Intake valves only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept	$ 120				
DVVL - EM	6 lost motion devices each operating 1 intake valve **pair** per cylinder. 6 actuators, drivers, harness. Intake valves only. Baseline DOHC valvetrain cost includes separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept		$ 180	$ 180		
DVVL - Electrohydraulic (EH)	4 lost motion devices each operating 1 intake valve **pair** per cylinder. 2 solenoids, drivers, harness. Intake valves only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept	$ 75				

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Variable Valve Lift (VVL)	Intake phasing costs must be added to all VVL and CVVL concepts.					
DVVL - EH	6 lost motion devices each operating 1 intake valve per cylinder. 3 solenoids, drivers, harness. Intake valves only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.		$ 115	$ 115		
DVVL - EH	6 lost motion devices each operating 1 intake valve per cylinder. 3 solenoids, drivers, harness. Intake valves only. Baseline cost is 2V per cylinder OHV using RHVL lifters.				$ 115	
DVVL - EH	8 lost motion devices each operating 1 intake valve per cylinder. 4 solenoids, drivers, harness. Intake valves only. Baseline cost is 2V per cylinder OHV using RHVL lifters.					$ 150
Continuously Variable Valve Lift (CVVL)	Ratio linkage including roller element for each **pair** of intake valves. 1 control shaft positioned by 1 electrohydraulic actuator per bank. Forked finger follower operates 1 pair of intake valves per cylinder. Hydraulic lash adjusters remain. Control of intake valves only. DOHC engines only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.	$ 150	$ 275	$ 275	$275+DOHC	$300+DOHC

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Cylinder Deactivation - Electrohydraulic						
Cylinder Deactivation - EH	6 lost motion devices each operating 1 valve **pair** 3 solenoids, drivers, harness. Deactivating all I & E valves in each cylinder for 1/2 of the engine cylinders. Excludes any necessary NVH improvements. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.		$ 115	$ 115		
Cylinder Deactivation - EH	6 lost motion devices each operating 1 valve 3 solenoids, drivers, harness. Deactivating all I & E valves in each cylinder for 1/2 of the engine cylinders. Excludes any necessary NVH improvements. Baseline cost is 2V per cylinder OHV using RHVL lifters.				$ 115	
Cylinder Deactivation - EH	8 lost motion devices each operating 1 valve 4 solenoids, drivers, harness. Deactivating all I & E valves in each cylinder for 1/2 of the engine cylinders. Excludes any necessary NVH improvements. Baseline cost is 2V per cylinder OHV using RHVL lifters					$ 150

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DVVL/Deact Combinations	Intake phasing costs must be added to all VVL combinations					
DVVL-EH with Cylinder Deactivation - EH	Add third step (closed) to intake valves on 1/2 the cylinders for deact - requires higher cost solenoids - 1 per deacted cylinder. Add 2-step on exhaust valves for deact on 1/2 the cylinders. Add 2-step solenoids to get to 1 per non-deact cylinder - no cylinder pairing possible. Can operate DVVL and / or Cylinder Deact independently at any time - a deactivated cylinder does not use DVVL while deactivated	$ 330	$ 200	$ 200	$ 200	$ 260
Camless Valve Actuation (CVA)						
Electromagnetic Actuation	Electromagnetic camless valve actuation. Assume 4 valves per cylinder. Includes control electronics. Expressed as net cost per engine.1 actuator per valve **pair**. Controller. Credit existing valvetrain. 42V is a requirement - these costs are excluded	$ 690	$ 780	$ 780	$ 1,100	$ 1,300
Electrohydraulic Actuation	Electrohydraulic camless valve actuation. Assume 4 valves per cylinder. 1 actuator per valve **pair**. Includes hydraulics and control electronics. Expressed as net cost per engine.	$ 575	$ 650	$ 650	$ 900	$ 1,100

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Variable Geometry Turbocharging	VGT gasoline turbo, charge air cooler, piston upgrade, piston cooling, steel crankshaft, cooling system upsize, plumbing, rings, pressure sensor & bearing upgrade. Excludes any needed increase in transmission torque capacity or modifications to aftertreatment system	$ 400	$ 400	$ 400	$ 400	$ 400
Electric Assist Turbocharging	Waste-gate gasoline turbo with 12V EAT functionality at 800-1500W consumption. Includes charge air cooler, piston and ring upgrade, piston cooling, steel crankshaft, cooling system upsize, plumbing, head gasket upgrade, pressure sensor &. bearing upgrade. Excludes any needed increase in transmission torque capacity or modifications to aftertreatment system	$ 475	$ 475	$ 475	$ 475	$ 475
Gasoline Engine Downsizing Credits	These credits apply only when the baseline vehicle gasoline engine is replaced by another gasoline engine of the type described for each credit. For the study AVL and NESCCAF models/scaled turbo gas engines at 65%, aggressive hybrids at 63% and moderate hybrids at 74% to these credits can be applied to those vehicle packages.					
Downsizing credit	L4 DOHC 4V remains L4 DOHC 4V	na				
Downsizing credit	V6 DOHC 4V moves to L4 DOHC 4V		$ (700)			
Downsizing credit	V6 DOHC 4V moves to L5 DOHC 4V		$ (550)			
Downsizing credit	V8 DOHC 4V moves to L4 DOHC 4V			$ (700)		
Downsizing credit	V8 DOHC 4V moves to L5 DOHC 4V			$ (550)		
Downsizing credit	V6 OHV 2V moves to L4 DOHC 4V				$ (200)	
Downsizing credit	V6 OHV 2V moves to L5 DOHC 4V				$ (50)	
Downsizing credit	V8 OHV 2V moves to L6 DOHC 4V					$ (300)

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		2.2L DOHC 4V A4 FWD Cavalier (SC)	3.0L DOHC 4V A4 FWD Taurus (LC)	3.4L DOHC 4V A4 RWD Tacoma (ST)	3.3L OHV 2V A4 RWD Town & C (MV)	5.3L OHV 2V A4 AWD Sierra (LT)	
Supercharging	Advanced supercharger including charge air cooler, piston and ring upgrade, piston cooling, steel crankshaft, bypass and plumbing, head gasket upgrade, pressure sensor & bearing upgrade. Excludes any needed increase in transmission torque capacity.	$ 435	$ 435	$ 435	$ 435	$ 435	
Variable Charge Motion Direct Injection (DIG) ◻ Stoichiometric	Active intake port tuning utilizing hydraulically actuated "bumps" in each port.	$ 30	$ 50	$ 50	$ 50	$ 60	
Direct Injection (DIG) - Lean Burn Stratified Charge	Wall-guide DIG 90-100 bar pressures. Excludes all modifications to base engine	$ 135	$ 185	$ 185	$ 185	$ 210	
Lean Burn DIG Aftertreatment Cost Delta	AVL designed 3.0L V6 with 3.73 g/mi engine-out NOx. System includes inactive exhaust cooler. Scaled using baseline engine displacements	$ 385	$ 500	$ 570	$ 560	$ 900	
Gasoline HCCI (AVL CSI System)	AVL CSI System: Wall-guide DIG 90-100 bar, ion sense or virtual cylinder pressure-sensing, intake phaser, DVVL/EH, supplemental EH exhaust valve operation for dilution management w/ high pressure oil pump and plumbing. Stoichiometric aftertreatment.	$ 400	$ 600	$ 600	na	na	
Variable Compression Ratio	Hydraulic pump, acutators, tilt design, can move CR from 7-10	$ 320	$ 380	$ 380	$ 380	$ 440	

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Baseline high-speed Diesel Engine Displacement	Downsized DOHC 4V turbo diesel engines modeled by AVL to provide equivalent performance to each baseline gas engine.	1.78L L4	2.40L L4	2.28L L4	2.31L L4	3.85L L6	
Baseline high-speed Diesel	DOHC 4V turbo diesel. Common rail, ~1,800 bar, Piezo-actuated injectors, VNT, cooled EGR. Includes downsizing credit. Excludes any needed increase in transmission torque capacity.	$ 1,000	$ 300	$ 300	$ 800	$ 950	
Baseline diesel aftertreatment Cost Delta over stoich.	AVL designed 2-leg system revised to single leg per MECA. Scaled from 2.8L V6 with 0.32 g/mi engine-out NOx.	$ 500	$ 575	$ 600	$ 600	$ 1,000	
Diesel Advanced Multi-Mode	DOHC 4V turbo diesel. Common rail, ~1,800 bar, Piezo-actuated injectors, VNT, cooled EGR. Includes downsizing credit. Excludes any needed increase in transmission torque capacity.	$ 1,000	$ 300	$ 300	$ 800	$ 950	
Diesel Advanced Multi-Mode Aftertreatment Cost Delta	FEV-NREL APBF-DEC light duty advanced aftertreatment system (DEER 8-2003). Scaled from 1.9L engine containing 1 pre-cat (DOC + LNT functionality), 1 underfloor LNT and CDPF. MECA supplied PGM loadings expressed as a range.	$250-350	$300-450	$280-400	$285-400	$500-725	
Diesel Engine and Aftertreatment downsizing substitution for Aggressive Hybrid	Per NESCCAF design scaling of hybrid vehicles, use L4 DOHC 4V turbo diesel AMM for this large truck vehicle class but only with the aggressive hybrid drivetrain. Aftertreatment cost is included in this cost.					$ 900	

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Drivetrain Technologies							
Transmission	Conventional step gear	$ 100	$ 100	$ 100	$ 100	$ 100	
Transmission	Lepelletier gear set design	$ 50	$ 75	$ 75	$ 75	$ 80	
Continuously Variable Transmission (CVT)	Belt CVT. NESCCAF assumptions: Assumes competitive market for belt technology free of licenses and IP protection. Assumes global volume and capital infrastructure on par with step-gear transmissions.	$ 150	$ 175	$ 175	$ 175	na	
Automated Manual Transmission: 6 speed	6-speed, dual wet clutch, fully automated. Piece cost only - i.e., US manual transmission capacity does not exist vs. Europe	neutral	neutral	neutral	neutral	neutral	

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14V belt starter-alternator (idle off)	2kW machine. Includes inverter/controller, cable upgrade, belt tensioner upgrade. Credit alternator. Starter motor required for cold start. Maximim cylinder displacement = ~ 45L for warm re-start. Includes 14V Pb acid battery upgrade.	$ 200	na	na	na	na	
42 Volt BAS - Belt Drive w/ Idle Off	4kW machine. Includes belt upgrade, power electronics, DC-DC converter for split system. Liquid cooled electronics. Credit alternator and starter. Maintain starter motor for 5.3L cold crank. Excludes battery upgrade.	$ 450	$ 450	$ 450	$ 450	$ 600	
42 Volt ISG w/ Launch, Regen, Idle Off	10kW motor, flywheel integration, power electronics, DC-DC converter split sytem, liquid cooled, credit starter and alternator. Excludes battery upgrade.	$ 800	$ 800	$ 800	$ 800	$ 800	
42V system lead acid battery for BAS	36V 20Ah advanced adsorbent glass mat (AGM) lead acid battery - 72 KwHr. Targeted primarily for the BAS system above.	$ 120	$ 120	$ 120	$ 120	$ 120	
42V system lead acid battery set for ISG	36V 55Ah advanced adsorbent glass mat (AGM) lead acid battery set - 1.98 KwHr. Targeted primarily for the ISG system above.	$ 330	$ 330	$ 330	$ 330	$ 330	
42V system NiMH battery upgrade	Full battery pack including 36 cells, 43.2V, 14A-h, 605 KwHr capacity, 2117 kJ energy (Ref: SAFT Vh10/42, air cooled (40C) 36XVH4/5SF) for BAS or ISG.	$ 400	$ 400	$ 400	$ 400	$ 400	
42V system NiMH battery upgrade	Full battery pack including 36 cells, 43.2V, 45.8 A-h, 1.98 KwHr capacity for ISG.	$ 1,090	$ 1,090	$ 1,090	$ 1,090	$ 1,090	

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Original Moderate / Motor Assist Hybrid Mechanizations	Based upon the Honda Insight architecture with design changes. Small car uses 30Kw PM mogen, 144V .9 KwHr NiMH battery pack. All other vehicles use 50Kw PM mogen, 288V 1.8 KwHr NiMH battery pack. All vehicles include costs for CVT transmission, power electronics w/ 1 inverter and controls. **Excludes cost of replacement battery pack.**	$ 2,050	$ 2,750	$ 2,750	$ 2,750	$ 2,750	
Original Aggressive / Fully Integrated Hybrid Mechanizations	Based upon '04 Toyota Prius architecture with design changes. All vehicles use 30 Kw PM generator / starter, 50 Kw PM motor and 288V 1.8 KwHr NiMH battery pack. Cost includes hybrid continuously variable auto transmission, power electronics w/ 2 inverters and 1 dc dc voltage converter for 500V output and controls. Credit given for baseline vehicle starter and generator. **Excludes cost of any replacement battery pack.**	$ 3,000	$ 3,000	$ 3,000	$ 3,000	$ 3,000	

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Revised Moderate / Motor Assist Hybrid Mechs	04 Honda Civic Hybrid architecture scaled by NESCCAF to fit each vehicle class. Net cost includes a conventional transmission, NiMH battery pack at 144V, control and power electronics including 1 inverter for 144V system, 1 permanent magnet motor/generator. Credit given for baseline vehicle generator. **Excludes cost of replacement battery pack.**						
	Battery pack 9.0 Ah, mogen 15 Kw, CVT transmission	$ 1,650					
	Battery pack 12.0 Ah, mogen 20 Kw, CVT transmission		$ 2,100		$ 2,100		
	Battery pack 12.0 Ah, mogen 20 Kw, CVT transmission. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.			$ 2,100			
	Battery pack 15.0 Ah, mogen 25 Kw, 6 speed automatic transmission. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.					$ 2,400	

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Revised Aggressive / Fully Integrated Hybrid Mechs	04 Toyota Prius hybrid architecture design scaled by NESCCAF to fit each vehicle class. Net cost includes continuously variable hybrid transmission, NiMH battery pack at 201.6V, control and power electronics including 2 inverters w/ 1 dc dc converter for 500V system voltage, 1 permanent magnet generator/engine starter, 1 permanent magnet drive motor. Credit given for baseline vehicle generator and starter motor. **Excludes cost of any replacement battery pack.**					
	Battery pack 5.9Ah, drive motor 45Kw, generator 25Kw	$ 2,500				
	Battery pack 7.8Ah, drive motor 60Kw, generator 30Kw		$ 3,100		$ 3,100	
	Battery pack 7.8Ah, drive motor 60Kw, generator 30Kw. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.			$ 3,100		
	Battery pack 10.4Ah, drive motor 80Kw, generator 40Kw. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.					$ 4,000

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Other Load Reducing Technologies						
Advanced Power Steering						
Electrohydraulic power steering (EHPS)	If 14V electrical system, EHPS required for large truck case					$ 60
Electric power steering (EPS)	14/42V EPS. 42V is requirement for large truck case EPS.	$ 20	$ 40	$ 40	$ 40	$ 40
Electric 42V Demand Water Pump	42V requirement for demand water pump.	$ 50	$ 50	$ 50	$ 50	$ 50
High Efficiency Generator	80% high efficiency Lundell machine.	$ 40	$ 40	$ 40	$ 40	$ 40
Weight Reduction	Aluminum intensive vehicle - body. Cost per pound saved.	$ 2.50	$ 2.50	$ 2.50	$ 2.50	$ 2.50

Important Notes on Technology Cost Matrix

Vehicle manufacturer costs represent variable hardware cost delta over baseline technologies. R&D, capital investment and other costs associated with implementing new technologies are excluded.
Costs are forecast 2009+ at assumed high volume levels. See Methodology Section for full description.

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